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31JUL00 E556744-6 000239
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2. Patent application number *(The Patent Office will fill in this part)* — 27 JUL 2000 — **0018576.9**

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

The University Court of the University of Glasgow
10 The Square
Glasgow G12 8DD

Patents ADP number *(if you know it)*

If the applicant is a corporate body, give the country/state of its incorporation

07411054001

4. Title of the invention — Improved Semiconductor Laser

5. Name of your agent *(if you have one)* — Cruikshank & Fairweather

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

19 Royal Exchange Square
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Patents ADP number *(if you know it)* — 547002

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Request for preliminary examination and search *(Patents Form 9/77)*	
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11. I/We request the grant of a patent on the basis of this application.

Signature Cruikshank & Fairweather Date 28.7.2000

12. Name and daytime telephone number of person to contact in the United Kingdom Dr David Moreland 0141 221 5767

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IMPROVED SEMICONDUCTOR LASER

Background to the Invention

This invention relates to semiconductor lasers, and in particular, though not exclusively, to a semiconductor laser which uses a combination of gain profiling, and Quantum Well Intermixing (QWI) and advantageously a wide optical waveguide (WOW) to provide a high power semiconductor laser device which has high brightness and good beam quality.

Semiconductor lasers are commonly used in a number of applications, e.g. computer CD ROMs and compact disc players. High power semiconductor lasers are also used in solid-state laser pumping materials processing and medical applications. (A semiconductor laser producing more than a few hundred milliwatts of light is normally termed a high power device).

However, previous high power semiconductor laser devices have suffered from a number of problems such as poor beam quality and low brightness. The output power is also limited mainly due to interactions between the optical field and the laser facet (mirror).

The laser facet is cleaved semiconductor and as such contains a high density of vacancies and broken bonds which can lead to the absorption of generated light. Light absorbed at the laser facet generates heat as excited carriers recombine non-radiatively. This heat reduces the semiconductor bandgap leading to an increase in absorption inducing thermal runaway which results in Catastrophic

Optical Mirror Damage (COMD).

Many schemes have been suggested and implemented to increase COMD levels. These, for example, include facet passivation by chemical treatments and bandgap widening in the mirror regions. Bandgap widening can be achieved by re-growth processes. However, all of these schemes have proved complicated and unreliable with no single process being widely adopted.

Therefore, to produce high powers without suffering from COMD, manufacturers have previously tended to increase the width of the laser aperture. Although this increases the overall power output of the semiconductor laser, the amount of power per unit width emitted from the laser aperture is in effect reduced. Although this method does produce higher power, it is accompanied by a number of disadvantages. These disadvantages include a reduction in the brightness of the device, a reduction in the quality of the laser output beam (i.e. loss of spatial coherence), and it is also more difficult to dissipate heat out of the active region of the device.

One of the reasons why the beam quality of high power devices is poor, is due to the interaction of carriers with light in the active region of the device. These interactions take the form of spatial hole burning and self-phase modulation, which tend to induce changes in the refractive index. These changes in the refractive index allow modes higher than the fundamental mode to propagate resulting in a break-up of the near-field (filamentation)

and hence broadening of the far-field.

It is an object of at least one aspect of the present invention to obviate or mitigate one or more of the aforementioned problems and disadvantages of the prior art.

It is a further object of at least one aspect of the present invention to provide a semiconductor laser device which has high brightness and good beam quality.

Summary of the Invention

According to one aspect of the present invention there is provided a semiconductor laser device providing gain profiling, and quantum well intermixing (QWI). This combination of techniques produces a high power device with low loss integrated spatial filters.

The device therefore provides relatively high power and high brightness vis-a-vis prior devices.

Advantageously the device also provides a wide optical waveguide (WOW).

Preferably, the laser device is a fabricated compound semiconductor.

Preferably, the semiconductor device is fabricated on a GaAs III-V material system.

Preferably, the semiconductor device is fabricated from AlGaInP material.

Preferably, the semiconductor laser device is of a laser wafer structure.

Preferably, the semiconductor laser device has a layer structure incorporating a waveguide with an undoped high

index core region containing quantum wells, doped cladding regions and a p^{++} contact layer.

It is further preferred that the laser wafer structure contains a quantum well layer and is grown on a (100) Si doped GaAs substrate misorientated 10° to the [111] A direction. Preferably, the quantum well layers are a double quantum well layer of 670nm, emission wavelength epitaxial.

It is preferred that the laser wafer structure is grown by any suitable III-V semiconductor growth method.

Furthermore, it is preferred that the laser wafer structure is grown by metal-organic vapour phase epitaxy using a large III-V growth ratio or molecular beam epitaxy (MBE).

It is preferred that the structure consists of an n-doped GaAs buffer layer, an n-doped low refractive index waveguide cladding layer, an undoped high index waveguide layer, a p-doped low index upper cladding layer, a p-doped low index barrier reduction layer, a p^{++} doped GaAs capping layer, a dielectric insulation layer and a p-type contact.

It is even more preferred that the structure consists of a 500nm Si doped($3x10^{18}cm^{-3}$) GaAs buffer layer, a 1.0μm Si ($6x10^{17}cm^{-3}$) doped $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ lower waveguide cladding layer, a 600nm undoped $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P$ waveguide layer, a 1.0μm Zn ($6x10^{17}cm^{-3}$) doped $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ upper cladding layer, a Zn ($2x10^{18}cm^{-3}$) doped $Ga_{0.5}In_{0.5}P$ barrier reduction layer and a 300nm Zn ($>1x10^{19}cm^{-3}$) doped GaAs capping layer.

Preferably, there are a number of low bandgap quantum wells centrally placed in the undoped waveguide layer.

Preferably, the low bandgap quantum wells are two strained 6.8nm wide $Ga_{0.5}In_{0.5}P$ quantum wells and an undoped layer is a 15nm $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P$ barrier layer.

It is further preferred that the device consists of three separate sections:

a middle section which has a bandgap equivalent to the grown material, and

two outer sections which are both intermixed and passive, and the bandgap of which has been blue shifted which makes them transparent to the light generated in active regions.

Preferably, the middle section is injected with current and provides the gain of the device.

It is even more preferred that the middle section is a shaped contact using a geometric pattern, wherein the shape of the contact is selected to allow for matching of the optical mode and gain of the structure.

A further preferred embodiment is if the contact is shaped in a half-tone, finger pattern, triangular or Gaussian distribution.

It is also preferred if one of the passive sections is short, for example 1-100μm, and acts as a NAM allowing high output powers at the device facet and the other passive section is long, for example, 1mm and operates as a spatial filter.

It is also preferred if both passive sections are short whereby both sections act as a NAM and even higher power outputs are obtained. Preferably, the short passive

sections are 1-100μm long.

According to a second aspect of the present invention there is provided a method of fabricating a device according to the first aspect.

According to a third aspect of the present invention there is provided a method of using a device according to the first aspect.

Brief Description of the Figures

An embodiment of the invention will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 is a representation of the interaction between the optical field, carrier profile and contact shape;

Figure 2 is a representation of QWI;

Figure 3 is a representation of the optical field within a WOW;

Figure 4 is a perspective view of a semiconductor laser device according to an embodiment of the present invention;

Figure 5 is a side view of the semiconductor laser device as shown in Figure 4; and

Figure 6 is a top view of the semiconductor laser device as shown in Figures 4 and 5.

Detailed Description

One method used in the present invention to provide a semiconductor laser with both high power and high brightness is an Extended Cavity Laser (ECL) using QWI. Using this method, it is possible to produce bright single lobed far-fields by integrating slab waveguide sections onto broad area lasers (e.g. oxide stripe lasers). These effectively act as spatial mode filters incorporating what is essentially a diffractive region within the laser cavity promotes laser operation on a single spatial mode. The interaction of carriers with light in the device induces changes in the refractive index, and as a result light filaments form. Due to these high refractive index changes associated with the filaments, light influenced by the filaments experiences larger diffraction angles than the fundamental mode of the device. Therefore, the filaments experience greater diffraction losses than the fundamental mode as they propagate across the slab waveguide region. The fundamental mode will therefore have a greater overlap with the gain region and be selectively amplified. Although these ECL devices produce a good quality beam, using present production methods, they are limited to relatively low output powers. The limitations arise from reliability problems with QWI resulting from the dielectric cap materials (such as SrF_2) used and the high temperature anneals involved (>900°C). Although this device has been produced by using a new QWI process, due to high losses in the passive sections output, the external efficiency is low and thus output power is limited.

A further method used in the present invention to provide a high power semiconductor laser device is by using the (WOW) concept. High power semiconductor laser devices have previously relied on standard wafer structures. These use the design principle of maximising the overlap of the optical mode and quantum wells (i.e. the gain) of the structure. This overlap is denoted as Γ.

WOW structures (also known as large optical cavity (LOC)), have attempted to overcome previous problems by using structures that do not maximise Γ but minimise the loss of the structure (α). Following this route, it is possible to reduce the loss by more than the reduction of Γ which has the net effect of increasing the overall modal gain of the structure. Theoretically, these WOW structures can support more than one optical mode. However, since all of the WOW semiconductor structures gain is placed in the middle of the waveguide in the quantum wells, only the even modes see this gain and can effectively extract it. Also, as the order of the modes increase, they have more overlap with the doped cladding layers of the structure, and hence experience increased loss. Both of these factors ensure that the structure remains single moded in the vertical direction. Using these types of designs, it is possible to design devices that have single mode field profiles that are wider than normal, which increases the COMD level. The main use of WOW's in this device is to significantly reduce the losses in the passive regions making the device more efficient.

Although these WOW designs allow reduced optical losses, the device can still suffer from reduced performance at higher current injection levels. This is due to the fact that fundamental modes of broad area semiconductor layers have a Gaussian distribution of both the near and far-fields, whereas the injected carriers and thus the gain profile have a "top-hat" distribution.

Another method used in the present invention to seek to enhance the beam profile from semiconductor lasers is to use a technique known as gain profiling. The fundamental mode of broad area semiconductor layers have a Gaussian distribution of the near and far-fields. Gain profiling uses various methods to match the spatial distribution of injected carriers (and therefore also the gain) to the optical field distribution. This allows the fundamental mode to be selectively amplified in the laser resonator. Various schemes have been proposed and demonstrated. These include, for example, shaping contacts using half-tone or truncated finger designs where the spacing between contacts is of the order of the diffusion of the electrical carriers injected into the structure.

In a broad area semiconductor laser the fundamental distribution of light in the plane of the injection contact is Gaussian shaped. However, as higher currents are injected the mode breaks up and filaments form, which decreases the brightness of the laser. This is because the contact is typically a rectangular shape, which gives rise to a rectangular profile of injected carriers, which is

the subsequent profile of the gain within the device. Therefore the overlap between the gain and the fundamental mode of the optical field does not match which leads to the fundamental optical mode not extracting the gain efficiently, resulting in a build up of excess carriers. These excess carriers induce complicated nonlinear interactions within the device, and the optical field becomes irregular and forms filaments which as well as degrading the beam quality of the device, these filaments can induce large localised intensities resulting in COMD. To prevent this occurrence, it would be advantageous to match the gain with the required optical field. A method for doing this is to inject the required amount of carriers in to each part of the contact to give the correct spatial distribution of carriers. One way of achieving this is to utilise a shaped contact on top of the device. This works by using electrical contacts which have both carrier injection and non-injection areas possessing dimensions that are of the same order of the carrier diffusion within the waveguide layers. As a result, as the carriers diffuse into the device they spread out to form a continuous sheet of carriers that has a density which is graded to match the fundamental optical mode. The best shape of contact is one that generates a Gaussian distribution of carriers, however as this can be quite difficult to generate, other shapes have been proposed including triangular and truncated triangles as these offer easier options for fabrication.

The passive sections of the ECL have one other

advantage in that they operate as non-absorbing mirrors (NAM's) which enables higher laser diode output powers to be obtained due to the mirror facet being transparent to the generated light. COMD levels can then be raised since there is reduced absorption of light at mirror facets, which avoid thermal runaway of temperature. In standard devices (without NAM's) current flow through the mirror region also reduces the bandgap whereas turn increases in absorption are avoided through the use of NAM's as they are not subject to current injection. NAM's are implemented in many formats with some degree of success. These implementations have typically relied on some type of Impurity Induced Diffusion (IID) which has proven successful for increasing the bandgap, but suffers from free carrier absorption and is therefore limited to producing relatively short NAM sections. It is also extremely difficult to perform IID in the AlGaInP material system due to its very high thermal stability.

Although these passive sections are low loss through the use of QWI, in standard single mode laser structures the overlap of the optical field with the waveguide cladding regions are large. This can lead to relatively high waveguide losses for two reasons. Firstly, the passive regions are intentionally doped to provide a p-n junction and therefore contribute to the free carrier absorption of the waveguide. Secondly, the refractive index fluctuations at the interface between the waveguide core and cladding causes scattering losses.

Figure 1 shows the overlap between the gain and the fundamental mode of the optical field. Figure 1(c) shows the situation where the gain does not match the fundamental mode of the optical field. Using a shaped contact as in Figures 1(a) and 1(b), a better overlap is obtained.

Figure 2 shows the effect of QWI whereby the wells and barriers of quantum well structures are intermixed. As can be seen in Figure 2, the QWI smears out the energy profile of the two quantum wells reducing the quantum confinement of the wells within the laser structures, and simultaneously incur the effective band gap of the quantum wells which also lowers the optical losses in these sections. In the case of impurity free intermixing there is no added optical losses through the incorporation of impurities that add to free carrier absorption.

Figure 3 shows the wide optical waveguide structure wherein the overall modal gain is increased. Although the WOW structures can support more than one optical mode, because all of the gain is placed in the middle of the waveguide i.e. in the quantum wells, only the even modes see this gain and can extract it effectively. Furthermore, as the order of the modes increase, they have more overlap with the cladding layers of the structure and hence experience increased loss. As shown in Figure 3, this helps to ensure that the structure remains single moded in the vertical direction.

As shown in Figures 4 and 5, the semiconductor device 10 is formed from a laser wafer structure initially

fabricated in AlGaInP material. (However, it should be noted that other III-V semiconductor materials can also be used).

The laser wafer structure is a standard 670nm double quantum well layer which has been grown on a (100) Si doped GaAs substrate 12 misorientated 10° to the [111] A direction. The wafer may be grown by metal-organic vapour phase epitaxy, using a large III-V growth ratio. The misorientated GaAs substrate along with high growth temperature is used to inhibit the occurrence of long-range ordering.

The device 10 consists of, as shown in Figure 5, a bottom GaAs substrate 12 which has a depth of 500nm and is Si doped ($3x10^{18}cm^{-3}$). Above this GaAs substrate 12 there is a 1μm Si ($6x10^{17}cm^{-3}$) doped $(Al_{0.7}\ Ga_{0.3})_{0.5}In_{0.5}P$ lower waveguide cladding layer 14.

There is then a 600nm undoped $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P$ waveguide layer 16. Above the waveguide layer 16 there is a 1μm Zn($6x10^{17}cm^{-3}$) doped $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ upper cladding layer 18.

There is then a Zn($2x10^{18}cm^{-3}$) doped $Ga_{0.5}In_{0.5}P$ barrier reduction layer 20. On top of the barrier reduction layer 20 there is a 300nm Zn($>1x10^{19}cm^{-3}$) doped GaAs capping 22 (i.e. contact layer). Above this capping layer 22 there is a dielectric insulation layer 32.

As shown in Figures 4 and 5 on the top of the semiconductor device 10 there is a p-type contact 30.

As shown in Figure 2, within the waveguide region 16

there are two strained 6.8nm wide $Ga_{0.5}In_{0.5}P$ quantum wells 24. These quantum wells 24 are centrally placed and are separated by a 15nm $(Al_{0.3}Ga_{0.7})_{0.5}In_{0.5}P$ barrier.

Figure 6 shows the semiconductor device 10 consisting of in principle three sections 24, 26, 28. Two of these sections 24, 28 are intermixed and passive and have a high energy bandgap as compared to the As grown material in the middle 28. The blue shifting of the intermixed and passive sections 24, 28 render them transparent to light generated in the active region 26. In section 28, the first-order mode diffraction angle is shown in Figure 6.

In operation, the middle section 26 of approximately 100 x 1000μm is injected with current and provides the gain of the device. As shown in Figure 6 the middle section 26 has a shaped p-type contact formed from either a half-tone or finger pattern. The p-type contact 30 in Figure 5 does not show this shape). The shape of the p-type contact 30 is selected to enable matching of the optical mode and the gain of the structure. It can possess a triangular shape, Gaussian or any other geometrical distribution.

Although not shown in any of the Figures, one of the passive sections 24 may be short (10-100μm) and acts as a NAM allowing high output powers at the device facet. The other passive section 28 may be much longer, (approximately 1mm) and act as a spatial filter.

Both passive sections may also be short (10 - 100μm) to enable higher outputs to be obtained. Higher outputs are therefore obtained by having NAM's on the ends of the

fingers. There is however a decrease in the quality of the beam. The NAM's are too short to provide significant spatial filtering.

EXAMPLE

The semiconductor is fabricated using standard procedures.

To fabricate the ECL's, a sample may be cleaned and masked with photo-resist to protect areas where intermixing is not required, a layer of sputtered SiO_2 is then deposited onto the sample. Sputtered SiO_2 deposited on the masked regions is removed by lift-off in acetone and the whole sample is coated with a layer of electron beam or plasma enhanced chemical vapour deposition (PECVP) evaporated SiO_2 to protect the areas from which the sputtered SiO_2 was removed. The sample is then annealed in a Rapid Thermal Annealer (RTA). Photolithography and dry etching are used to define the gain sections on the middle area where QWI has not taken place. Finally the sample is thinned and p- and n-type contacts are deposited by electron beam evaporation and then annealed.

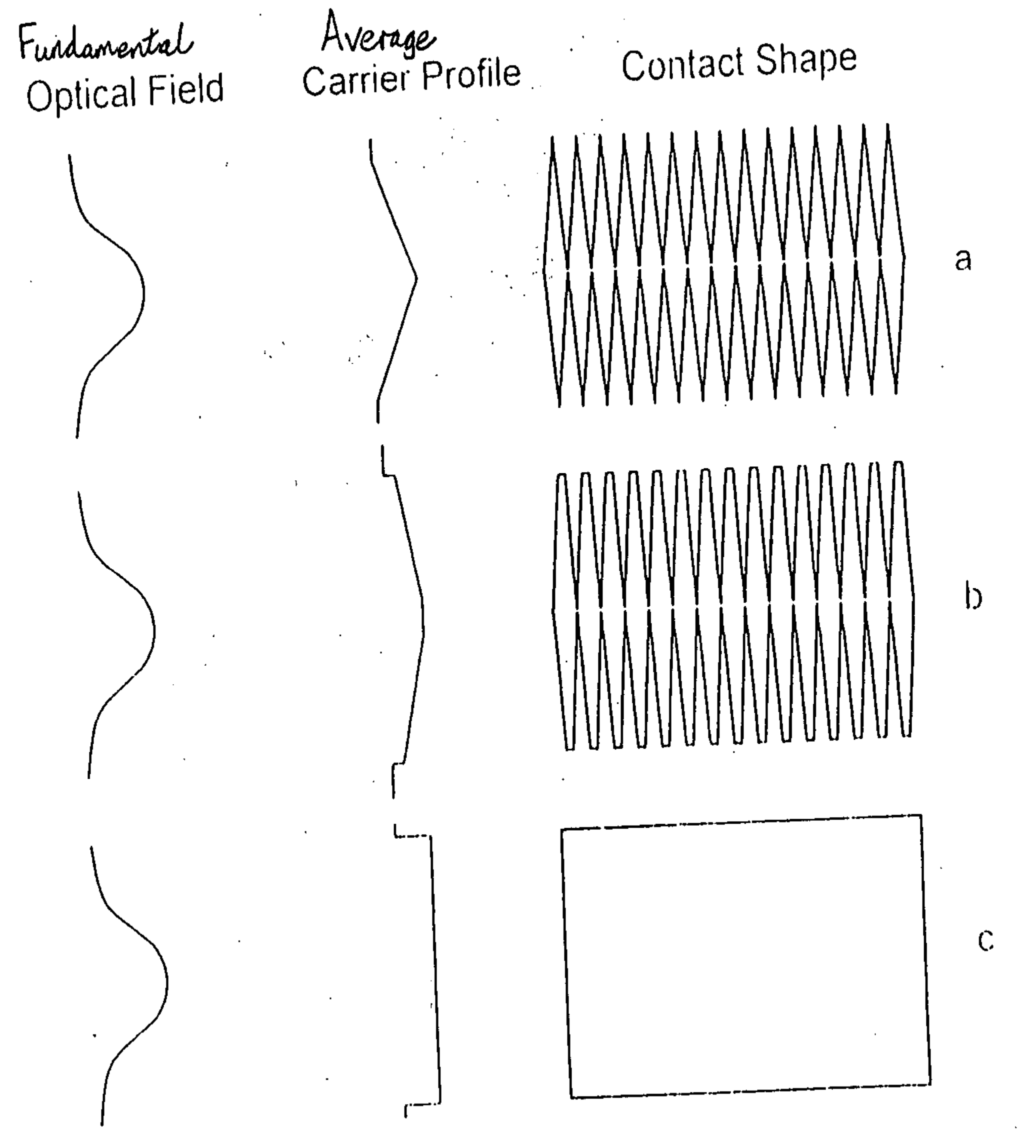
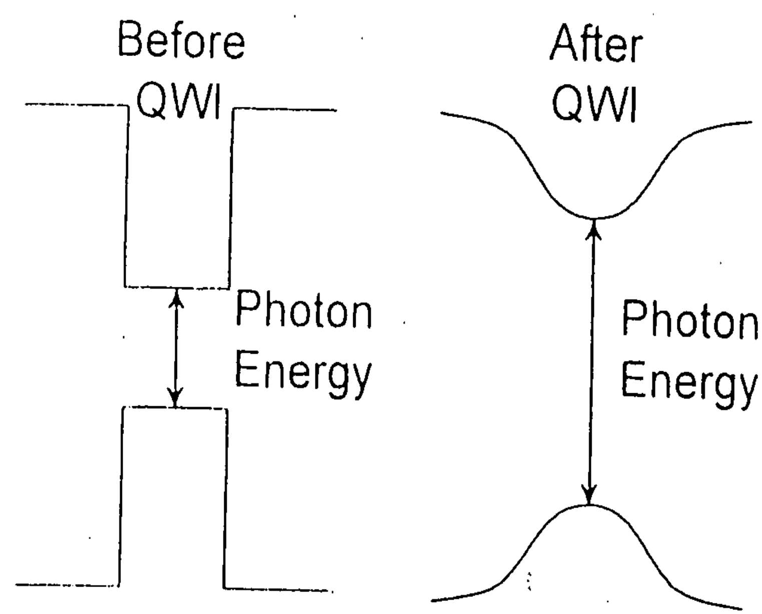

Fundamental
Optical Field
Average
Carrier Profile
Contact Shape
a
b
c

Figure 1.

Quantum Well Shapes

Figure 2.



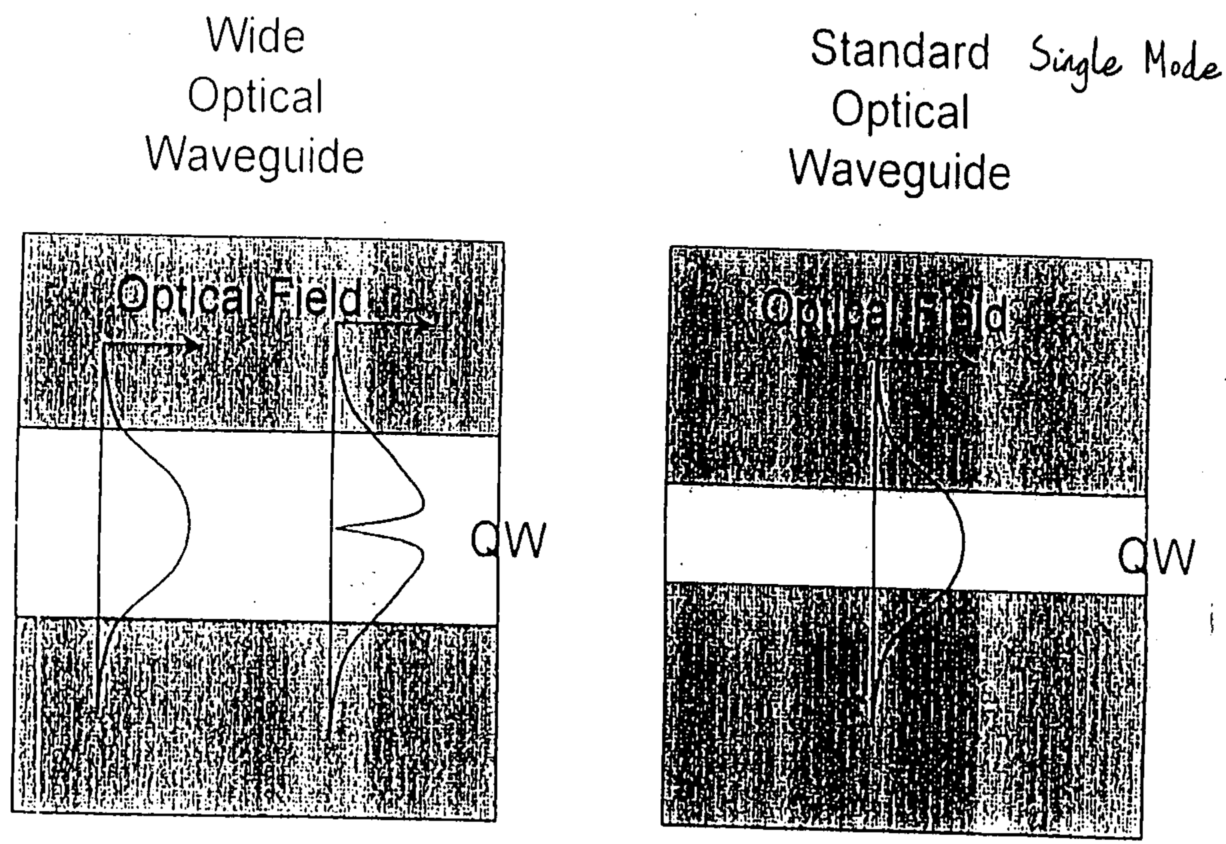

Wide
Optical
Waveguide
Optical Field
QW
Standard Single Mode
Optical
Waveguide
Optical Field
QW

Figure 3.

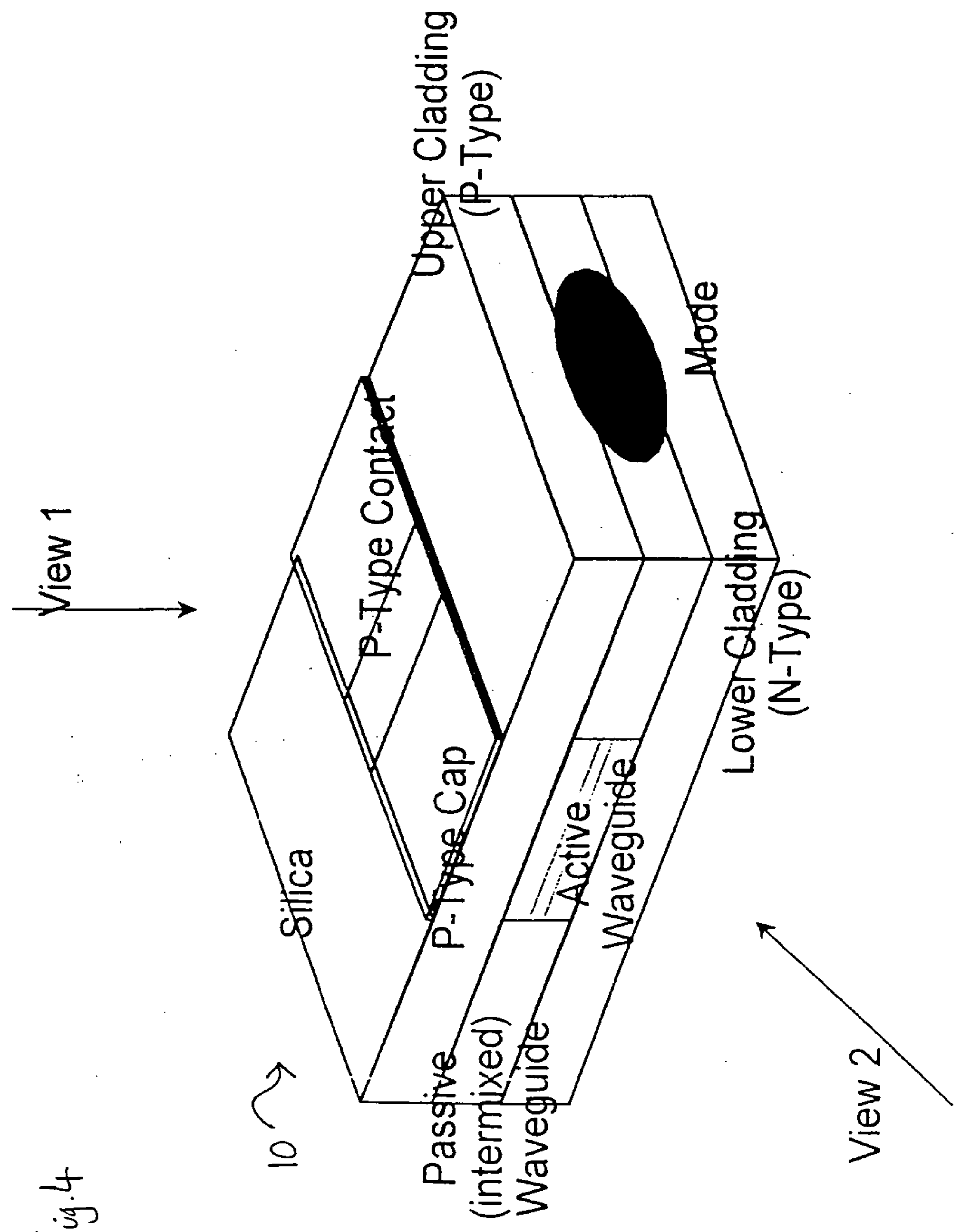
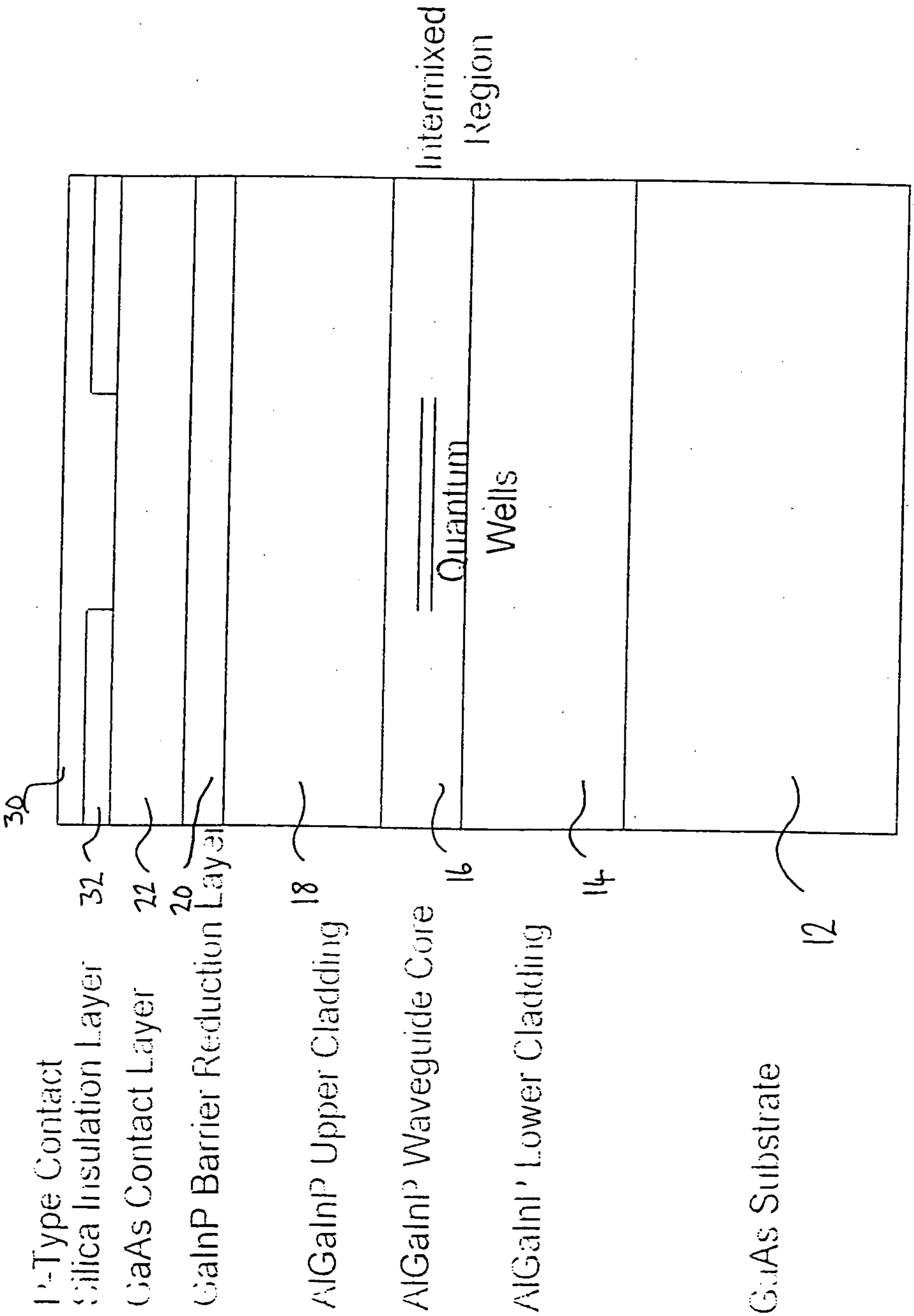

View 1
P-Type Contact
Upper Cladding
(P-Type)
Mode
Silica
P-Type Cap
Active
Waveguide
Lower Cladding
(N-Type)
Passive
(intermixed)
Waveguide
10
View 2

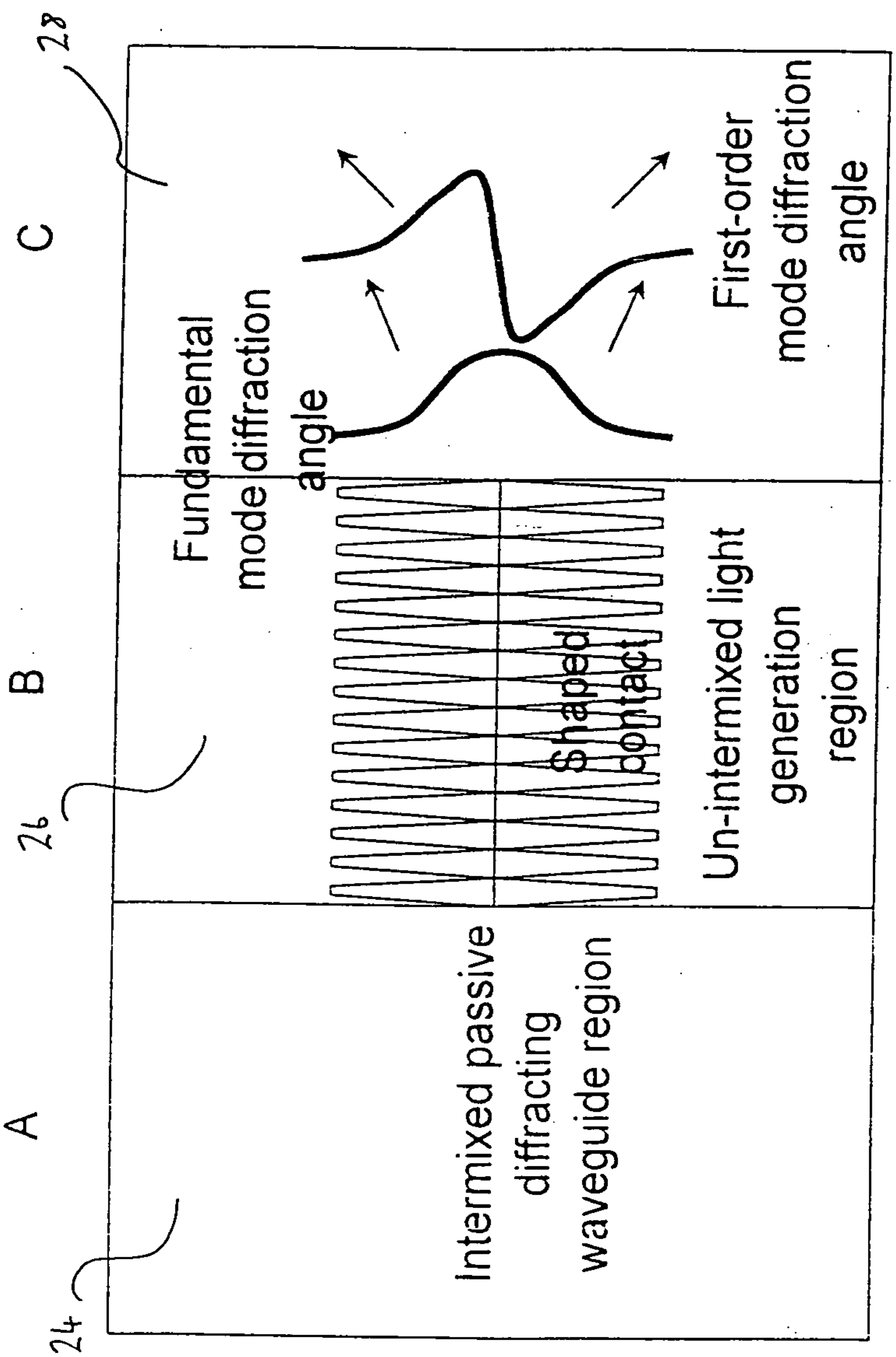
Fig. 4

Fig. 5



P-Type Contact
Silica Insulation Layer
GaAs Contact Layer
GaInP Barrier Reduction Layer
AlGaInP Upper Cladding
AlGaInP Waveguide Core
AlGaInP Lower Cladding
GaAs Substrate
Intermixed Region
Quantum Wells
30
32
22
20
18
16
14
12

Fig. 6


A
B
C
24
26
28
Intermixed passive diffracting waveguide region
Shaped contact
Un-intermixed light generation region
Fundamental mode diffraction angle
First-order mode diffraction angle

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